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COMPUTER-AIDED DESIGN (CAD) FOR INTEGRATED MICROELECTROMECHANICAL (MEMS) DEVICES

Analog Devices, Incorporated

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13. ABSTRACT *(Maximum 200 Words)*
The objective of this “CAD FOR Integrated MEMS Devices” research project was to develop MEMS CAD design and development tools that would facilitate the creation of behavioral models for complex MEMS devices. More complex and capable MEMS devices are becoming a reality to extend out country’s technological leadership in military and commercial electronics, which in turn would help maintain our military superiority. To this end, the project focused on creating a uniform design environment for the design and simulation of high-performance, complex integrated MEMS systems. The initial activity focused primarily on the MEMS systems design, however it became clear that incorporating integrated circuit simulations with the MEMS behavioral models was a priority. This provided more accurate simulations of the integrated MEMS systems as well as the environment they were intended to operate within. The resulting design environment provides the designer with an increased likelihood of functional first silicon. High performance MEMS devices such as accelerometers and gyros require the MEMS, circuits and their interactions to be fully simulated – primarily because MEMS devices exhibit fundamentally more complex interactions than those required in conventional electronic CAD.

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1 Technical Achievements

1.1 Objective

As often happens with long term programs the initial objectives and motivations evolved during the course of the MEMS CAD program. While the objectives did shift, the shift was more an expansion of the goals to increase the impact of this program to the MEMS design community as well as more fully realize the initial intension – MEMS CAD tools for highly complex, integrated MEMS systems.

1.1.1 Initial Objective

The initial objective of this project was to develop MEMS CAD design and development tools that would facilitate the creation of behavioral models for complex MEMS devices. More complex and capable MEMS devices were becoming required to extend our country's technological leadership in military and commercial electronics, which in turn would help maintain our military superiority. At that time no means was available to rapidly and accurately design integrate MEMS systems.

High performance MEMS devices such as accelerometers and gyros require the MEMS, circuits and their interactions to be fully simulated – primarily because MEMS devices exhibit fundamentally more complex interactions than those required in electronic CAD. These interactions are so complex that behavioral models were required; however, accurate behavioral models were not available in MEMS CAD tools at the beginning of this program.

To address the lack of adequate MEMS CAD tools, Analog Devices and Microcosm Technologies, worked together to develop a suite of CAD tools that provide a self-consistent modeling environment enabling the effective design, simulation, verification, and manufacturing of large, rigid, complex, MEMS devices. The program was broken into 3 major tasks: simulation, support, and evaluation (see Figure 1). Microcosm was responsible for most of the simulation tasks except for the Spice based system modeling, which was handled by Analog Devices. The support task was primarily developed at Analog Devices. Finally, the evaluation task was shared between both companies.

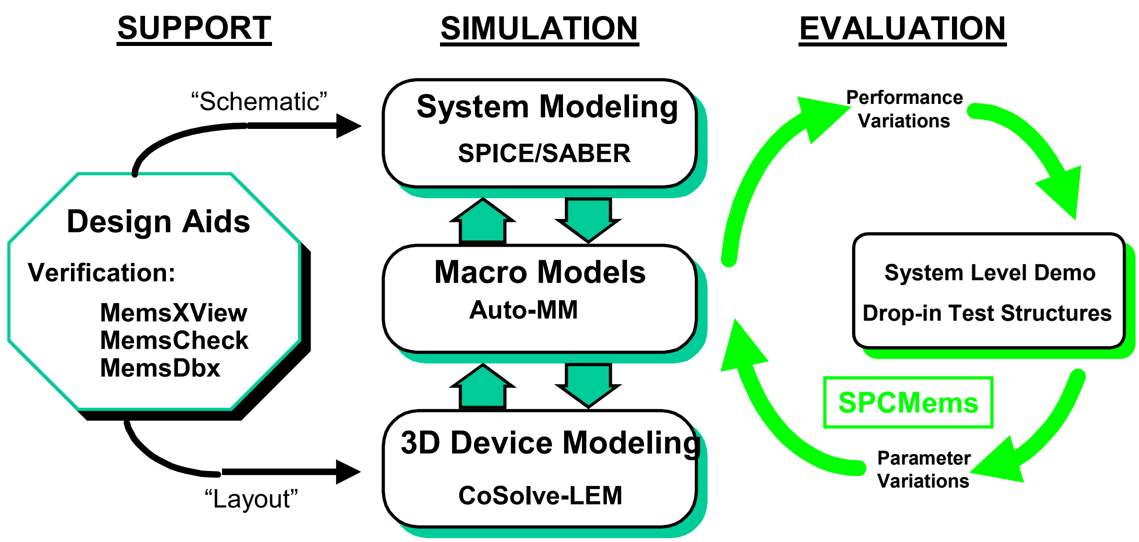


Figure 1: MEMS CAD program tasks.

The initial proposal was to create a MEMS CAD system based on automatically generated behavior models in Spice for easy incorporation into circuit simulations. However, this was changed to models based on the MAST™ language from Saber because Spice turned out to be too limiting especially for greater than 3 DOF models. The MAST™ models would be automatically generated behavioral models that were created from coupled mechanical finite element and electrostatic boundary element simulations.

1.1.2 Final Objective

During the course of this program the object expanded to create a uniform design environment for the design and simulation of high-performance, complex integrated MEMS systems. The stress was on "integrated MEMS" and primarily refers to the shift from Saber™ as the base HDL simulation tool to a Cadence/Spectre™ interface. While the initial objective focused primarily on the MEMS system design, it became increasingly clear that incorporating the integrated circuit simulations with the MEMS behavioral models was a priority. This would provide more accurate simulations of integrated MEMS systems as well as increase the likelihood of functional first silicon.

Cadence/Spectre™ is a much more widely used electronic CAD package for integrated circuit design so this was felt to be more relevant to the general integrated MEMS community. Saber was initially not designed as a circuit simulator like Spectre™, it was designed as a high level system simulator. This made Saber™ perfectly matched for the initial objective of a MEMS focused design flow, but ill suited to a higher-level integrated system design flow.

1.1.3 Note on Microcosm versus Coventor

During the course of this program Microcosm changed the company name to Coventor. Correspondingly the name of their software package was also changed from MEMCAD™ to CoventorWare™. Both names are used throughout this report, but refer to the same essential tools and code.

1.2 Major Accomplishments

1.2.1 Executive Summary

This program met almost all of its objectives. MEMS CAD tools were produced to create automatic behavioral models that were derived from FEM and BEM simulations of MEMS devices. The resulting software was made available to the MEMS community through the MEMCAD™ suite of tools. The MEMCAD™ tools are based on a Saber™ HDL simulation engine, which is well adapted for system level simulations (specifically MEMS). The program was divided in to three tasks: simulation, support and evaluation. The primary accomplishments of the simulation task were the creation of AutoMM™, which automatically generates 6 DOF macromodels, the improvement of the Cosolve-EM™ engine inside MEMCAD™ to solve large real world MEMS devices, the initial formation of the parameterized electro mechanical (PEM) behavioral model library (top-down design flow), and the implementation of a schematic to layout creation feature.

The support or verification task produced some useful design aids around a Cadence design environment: a symmetry/mass and connectivity checker. However, the initial goal of producing a full mechanical layout versus schematic (LVS) implementation was not achieved. An alternative approach was produced though that was based on a top-down design flow where the layout was generated from a schematic representation of the MEMS device (PEM library based).

In the evaluation task the new MEMS CAD system was applied to real world design problems: the ADXL190 and ADXL78. In addition, a series of test structures were designed and applied to several processes; however, a SPCMems tool was not developed.

Instead, AutoMM™ and the parameterized electromechanical library (PEM) allowed the user to explore the design space sensitivity to manufacturing variations such as beam width and curvature.

Towards the end of the project the resulting AutoMM™ and PEM models were ported from Saber/MAST™ to the Cadence/SpectreRF™ simulation environment. This was felt to be more useful for the general integrated MEMS community for the simulation of circuits with behavioral MEMS models. The Cadence environment produces accurate top-level circuit/MEMS simulations and should improve first silicon success because all complexities of the integrated MEMS design can be included (e.g. highly complex MEMS behavior as well as parasitic capacitance and resistance effects).

The major accomplishments of this program are organized into four categories:

- Saber based MEMS CAD tools – Simulation and Support Tasks
- Spice based MEMS CAD tools – Simulation and Support Tasks
- Successful applications of newly developed CAD tools – Evaluation Task
- Uniform design environment for MEMS and integrated circuits in the Cadence environment – Verilog-A models

Each of these accomplishments is described the following sections.

1.2.2 Saber Based MEMS Cadtool Development: MEMCAD™

Four different tools/features in MEMCAD™ can attribute much of their existence to this program. MEMCAD™ has evolved into CoventorWare™ in which all of the software products have been transferred and are available today. Most of the features described below were made available with the release of MEMCAD™ 4.0 in 1999.

1.2.2.1 AutoMM™

AutoMM™ was the first MEMS CAD tool to automatically extracts 6 DOF electro-mechanical reduced order models from a solid model representation of a MEMS device. This is also known as a bottoms-up design flow and has been used quite extensively in MEMS prior to this program, albeit in a manual mode. While 6 DOF macromodels can be generated the user can choose lower DOFs. This will greatly decrease the time required to create the macromodel. AutoMM™ was initially released as part of MEMCAD™, but is now available in CoventorWare/Builder™.

The method of AutoMM™ is outlined in Figure 2. First, the user generates a solid model from a layout and a process description file. Next, the user instructs AutoMM™ to

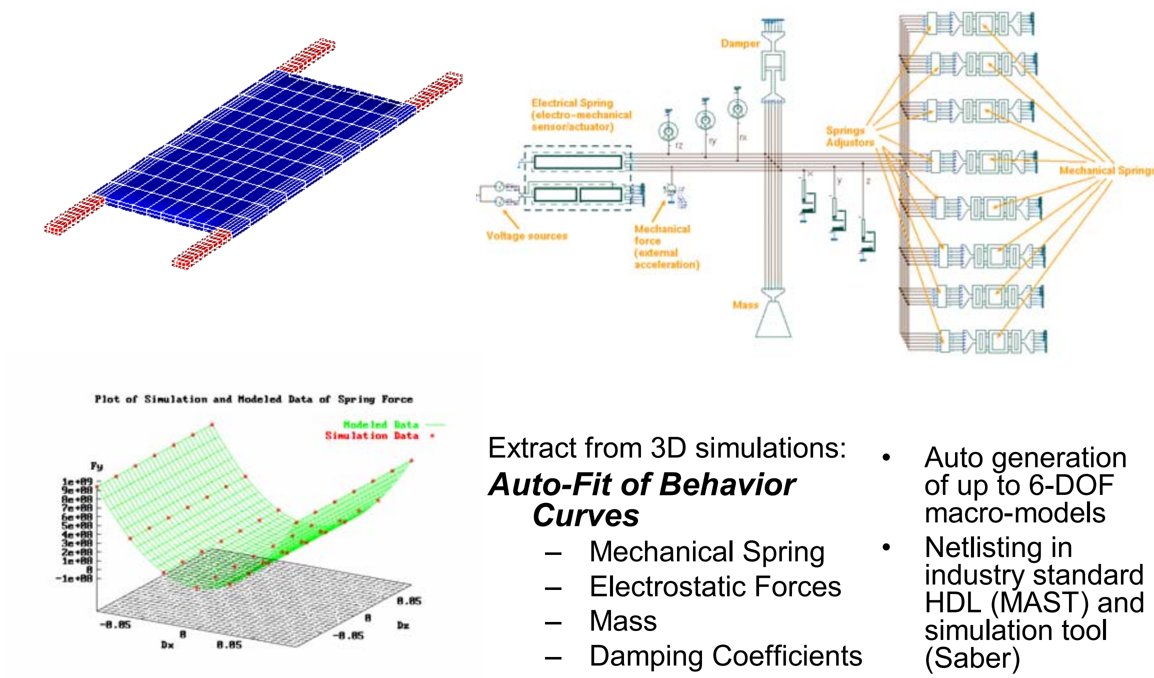


Figure 2: Outline of AutoMM™ process: Start with solid model of MEMS device. Simulate over a large space of deformations and curve-fit the results. The results are included as elements in a Saber™ based reduced order representation.

extract the spring, mass, damper or electrode macromodels of a given MEMS device, which is a accomplished through the corresponding FEM/BEM simulations including coupled domain simulations. The user is required to specify the boundary conditions of the solid model, the locations of loads and the range of desired deformations. A very large number of FEM/BEM simulations are required to curve fit the resulting responses to an acceptable level, but this is dependent on the desired number of degrees of freedom. The resulting macromodel is then made available for incorporation into any MAST™ HDL schematic. It is important to point out that each individual component (e.g. spring, electrode) must be independently extracted via AutoMM™. The idea isn't to generate a complete model of the entire device at once, but to break the macromodeling problem down to the individual components that can then be incorporated into a top-down simulation. A highly complex suspension is a good example of an AutoMM™ problem. Instead of using dozens or more beam PEM elements, the macromodel of the entire suspension can be extracted and substituted for all of the PEM elements. In addition to making the schematic much easier to understand it also speeds up the simulation in Saber.

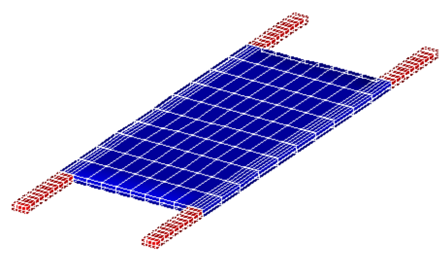
Since FEM/BEM simulations of complex MEMS devices are relatively slow it was imperative to improve the efficiency of the macromodel extraction. Two methods were implemented to speed up extraction. First, a latin hypercube sampling algorithm was tried, but while this method did improve efficiency it did not go far enough to allow AutoMM™ to tackle real-world problems like the ADXL76 accelerometer, which was one of the key goals of this project. The second method for numerical evaluation of a model for macromodel extraction was a stratified random sampling algorithm (SRS).

This improved extraction speed by a factor of 10-30x. Finally, to improve the accuracy of the resulting macromodels the curve fitting function class was expanded from polynomials to rational functions. This also helped reduce the number of points that were required for extraction, especially where large deformation effects become significant.

To verify the macromodels the same solid models were simulated with a full 3-D FEM simulation tool and the results compared with the Saber AutoMM™ macromodel results. Figure 3 shows two different geometries that were compared: a tethered plate and a micromirror. The results match very well to the full 3-D FEM simulations with typically a few percent difference between the macromodel and FEM results.

- Tethered plate

Degrees of Freedom	AutoMM	Full 3-D	% Error
Translational X	593.2K	583.5K	+1.66
Translational Y	3034.0K	3070.8K	-1.20
Translational Z	297.4K	304.8K	-2.44
Rotational X	672.5K	664.2K	+1.26
Rotational Y	169.0K	165.4K	+2.21
Rotational Z	1111.3K	1138.3K	-2.37



- Micromirror

DOF	25 Volts			150 Volts		
	F3D	AM	%E	F3D	AM	%E
Tz (nm)	-1.60	-1.56	2.5	-65	-60	7.7
Rx (μ rad)	2.526	2.46	1	102.5	89.6	12.6
Ry (μ rad)	40.95	39.5	3.5	1700	1550	8.8

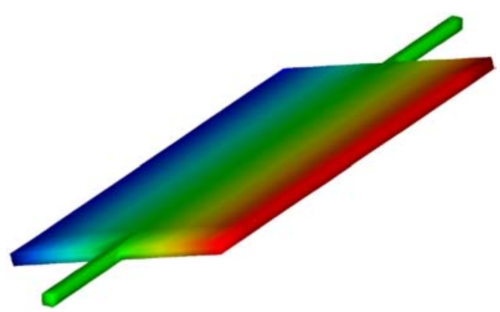


Figure 3: Comparison of AC response of AutoMM™ generated macromodel with full 3-D FEM simulation. Tethered plate – modal frequencies. Micromirror – static coupled electro-mechanics.

The tethered plate AutoMM™ macromodel was also used to verify the pull-in response of the macromodel with full 3-D coupled FEM simulations. It should be noted that the full 3-D coupled FEM simulations took ~100x longer to run. In this case there were four electrodes under the central mass, but only the lower left electrode had the voltage applied to it. As can be seen in Figure 4 the results agree very well.

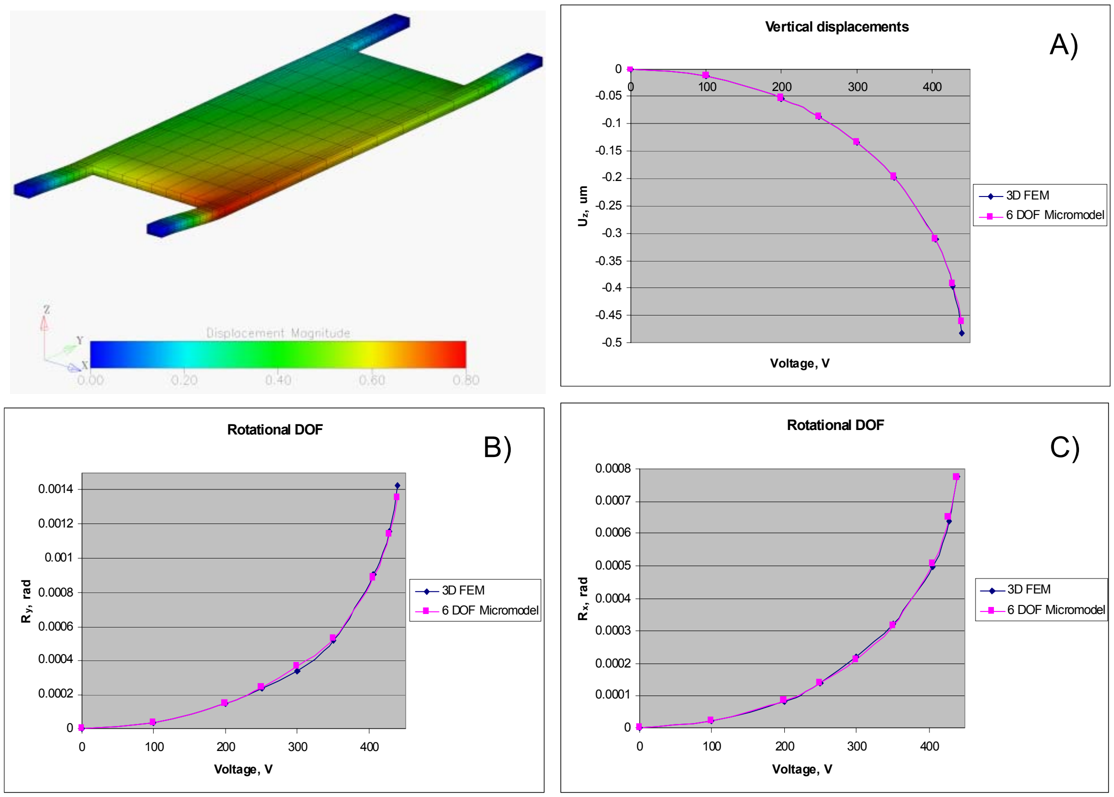


Figure 4: Comparison of pull-in analysis of AutoMM 6-DOF macromodel with full 3-D coupled FEM. The pull-down electrode was located under the lower-left corner of the tethered plate. A) z-displacement, B) y-rotation, C) x-rotation.

1.2.2.2 Cosolve-LEM™: Improvements and Enhancements

Cosolve-LEM™ solves problems in the electrostatic and mechanical domains by iterating between optimized solvers for each domain. The mechanical solver is finite element (FEM) based and is well understood. The electrostatic solver (MemCap™) is a boundary element solver (BEM) and was the focus of the effort in this project because the electrostatic problems are often much larger than the corresponding mechanical problems. Two separate meshes are created from the initial solid model, one FEM and one BEM. The two meshes are connected by sharing common vertices. This transfers the deformations between the two solvers.

To improve MemCap™ a pre-corrected FFT based algorithm was implemented. This added the ability to handle various Green's functions (e.g. ideal ground plane boundary conditions) and demonstrated better computational performance for most MEMS structures such as accelerometers. Memory management was also improved thus allowing the solution of up to 140,000 panel problems (Figure 5).

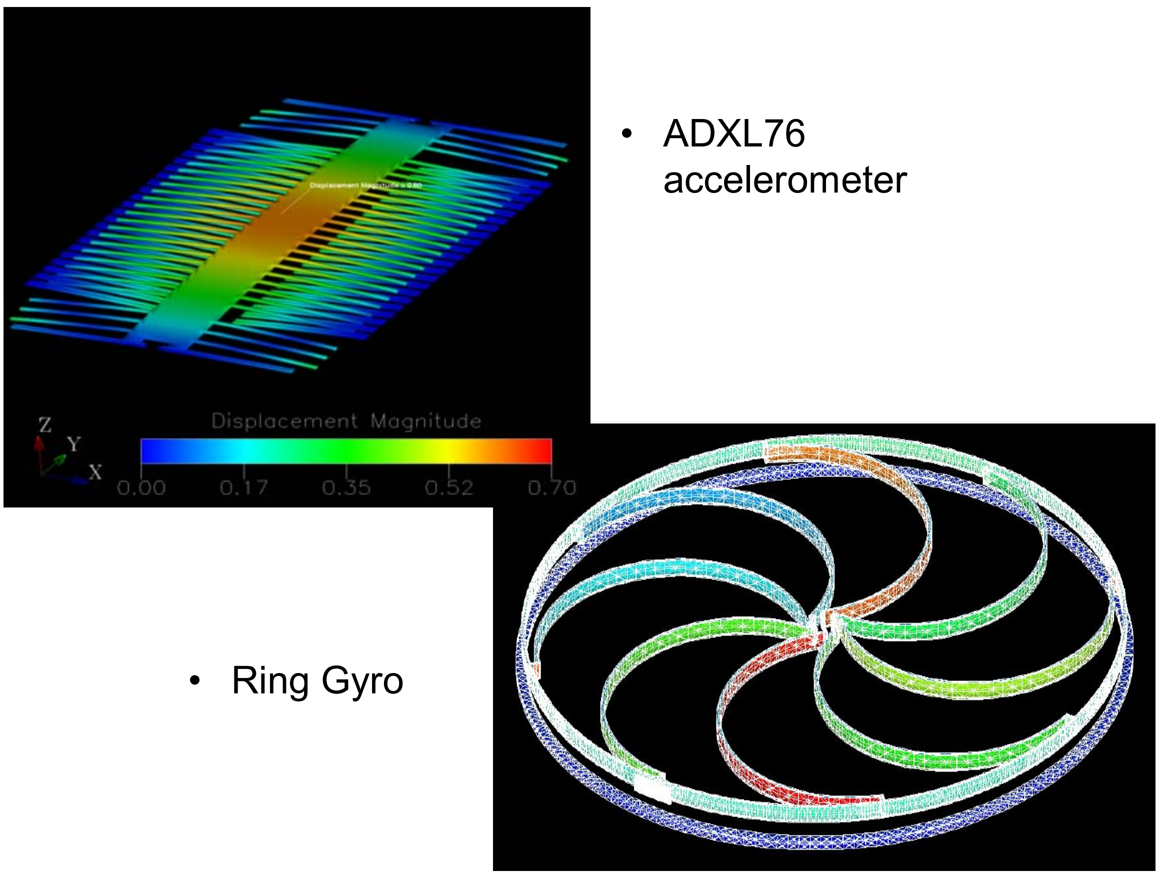


Figure 5: Simulation of highly complex MEMS devices in MEMCAD™: ADXL76 and a ring gyro.

In addition to improving the core MemCap™ solver several other enhancements were implemented. First, a tool was added for modeling resonant frequency shifts due to a DC bias voltage. This was implemented by an iterative relaxation procedure – start with the initial mechanical mode and frequency, extract the electrostatic stiffness, apply the electrostatic stiffness as a distributed spring to the initial state and repeat until a self-consistent solution is reached. Figure 6 shows a comparison of a MEMCAD™ simulation with experimental measurements of a simple fixed-fixed polysilicon beam.

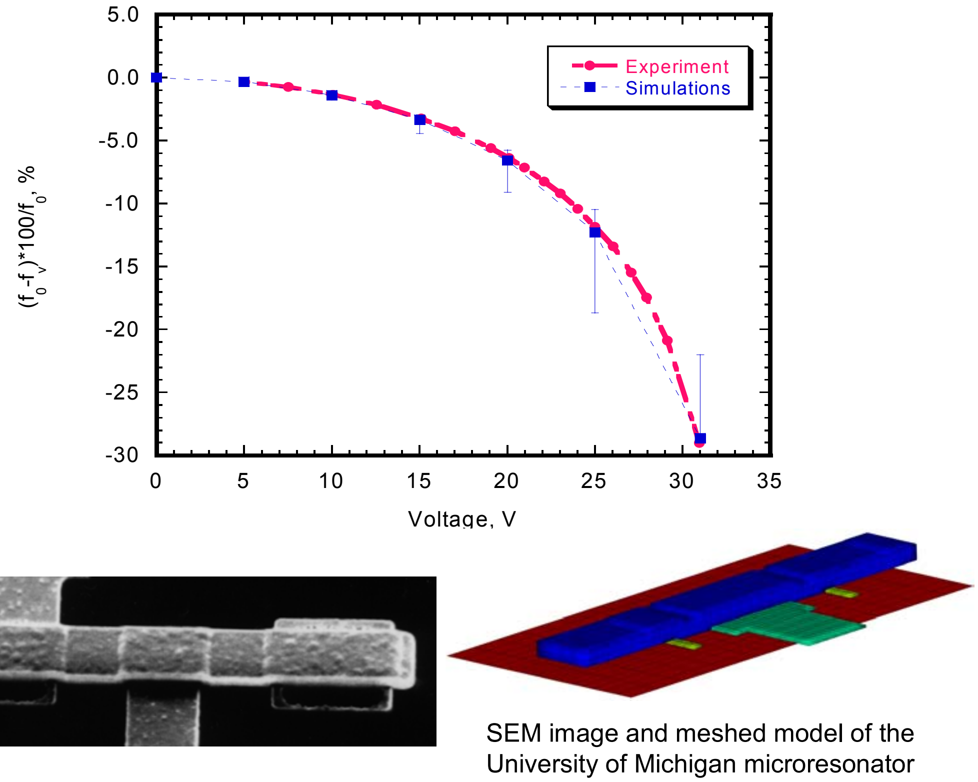


Figure 6: Predicted and observed frequency shifts for the resonant beam. Error bars show sensitivity to gap variation of ±6% around a gap of 0.08μm.

A tool for hysteresis behavior modeling in MEMS devices experiencing electrostatically induced contact/release interactions was also added to Cosolve-LEM™. Types of applicable MEMS devices are relays, switches and pumps. This tool provided directionality for the iterative action of the solver thus allowing the direction of the iteration to be changed (e.g. increasing then decreasing the voltage on a RF MEMS switch). Finally, we expanded the dimensionality of managed simulations with Cosolve-

LEM™ by incorporating voltage trajectories into solver's control space thus allowing voltage to be compared with other parameters such as geometry.

1.2.2.3 Parametric Electro-Mechanical (PEM) Library

AutoMM™ was the initial program in MEMCAD™ for the top-down design flow. It provides all the flexibility to handle large real-world problems like accelerometers and gyros. Unfortunately, to apply AutoMM™ to these problems takes considerable time because of the large number of FEM/BEM simulations required to achieve an accurate curve fit for the macromodel. Near the end of this program Microcosm began the development of the parameterized electro-mechanical models or PEM library. The PEM library was the natural extension of the AutoMM™ and was similar to NODAS (Verilog-A based) from Carnegie Mellon and to SUGAR from the University of California, Berkeley (Matlab based). The PEM models are fully 6 DOF and were implemented in the same industry standard HDL language as AutoMM™ – MAST™, from Saber™ (now owned by Avanti! ™). The PEM library has been migrated to CoventorWare/Architect™ and has lately been expanded by Coventor to include fluidic and optical elements.

A large variety of models were created and continue to be added to the library. One of the most basic elements is the mechanical beam element. In addition to the width, thickness and length, the independent slopes of each edge were also modeled thus permitting trapezoid cross-sections. Varying the height of each end of the beam and using several elements also models the out of plane curvature. Connecting many beam elements together can create more complex suspensions like serpentines or folded tethers, but will slow down the simulation. Alternatively, AutoMM™ can be used to model these complex suspensions (see Section 1.2.2.1). Damping was also added to the beam elements either as gas damping or modal damping. Finally, the mass of the beams is can be included for dynamic simulations.

Many other PEM elements must be included to simulate electromechanical MEMS devices. The mass was modeled either as a generic mass (lumped) or as plates (rigid or flexible). The thickness and shape of the mass is described in the parameters of the element. This way layout can be generated from these reduced order models. Electrostatic elements include 3 flavors of comb drives (lateral, longitudinal and curved) as well as a plate electrode. These models efficiently include fringing effects and are fully 6 DOF. Again, sidewall angle and etch hole density are included to create more realistic models of MEMS devices.

The test structures developed during this program were compared to the PEM library simulation results (as well as the AutoMM™ results). The comparison was very good with the error between AutoMM™, the PEM and measurements being typically <5-10%. This is quite good considering it is very difficult to measure your geometry to within better than 5%.

1.2.2.4 Schematic to Layout Creation

Mechanical layout versus schematic (LVS) has till today remained an unsolved problem. This project's initial attempt to solve the mechanical LVS problem is discussed in Section 1.2.3.2 and is based on the bottom-up design flow where the physical layout is extracted to form a reduced order model. Another method of performing mechanical LVS is to use a different design philosophy – a top-down design flow. Here the macromodel of the MEMS component is generated at the HDL design level using the

PEM library without any extraction of a physical layout back to the HDL level. This relies heavily on a highly accurate and calibrated PEM library.

To implement the layout generation physical layout characteristics must be added to the HDL models of the PEM library. While this is simple for beams and even electrostatic elements like combs, this can become very complex for mass elements. The mass elements are not typically a simple rectangle, but include arrays of holes, shoulders, and other protrusions for such purposes as accommodating design rules, creating limit stops, and anchor points for the suspensions.

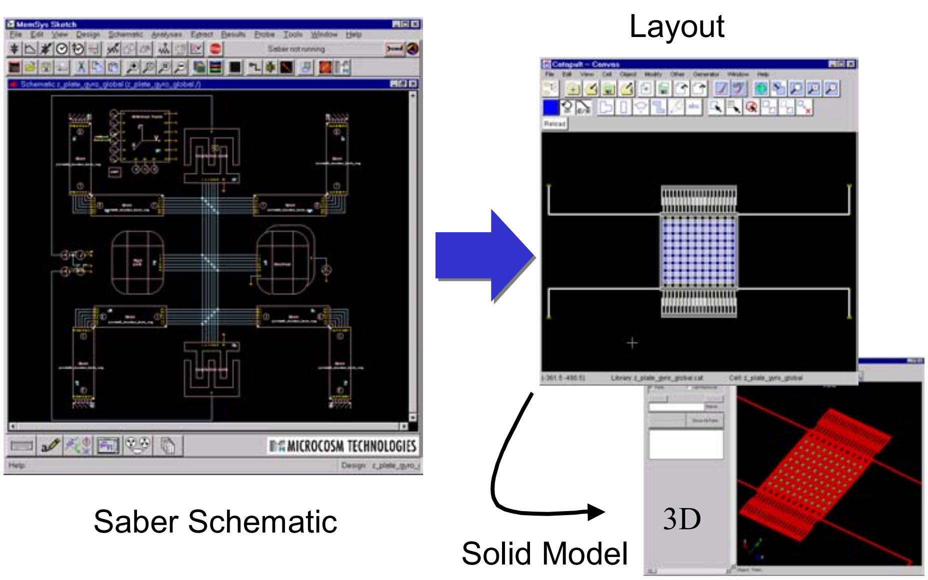


Figure 7: Automatic creation layout from a Saber™ schematic.

1.2.3 Spice Based MEMS Cadtool Developments

1.2.3.1 Mechanical schematic (ADICE/SPICE based models)

At Analog Devices, prior to the MEMS CAD program, an experienced MEMS designer must manually produce a simplified SPICE macromodel of the MEMS device, which is then incorporated into the circuit model of the complete system. This procedure is quite time consuming and can introduce significant errors. More importantly, the first-order nature of the SPICE model, underpinned by the inaccuracies in the underlying simulations, ensure a significant number of design-and-manufacturing iterations, which results in sub-optimal performance, higher costs, and greater time-to-market. As the complexity of the MEMS devices increase, this custom SPICE methodology has unfortunately becoming increasingly intractable.

The alternative that was developed at Analog Devices was to create a mechanical schematic representation of the MEMS device. In this representation the individual components (e.g. mass, spring, damping, capacitor, limit stop, boundary condition) are modeled in SPICE and are connected with wires that specify the mechanical and electrical connectivity of the device. The resulting mechanical schematic looks exactly like a circuit schematic except the wires represent force and position instead of current and voltage. Figure 8 shows the mechanical schematic of the ADXL76. The mechanical schematic is another top-down design flow, which is very similar to the PEM library approach developed in MEMCAD™, the difference being primarily the modeling language.

In the mechanical schematic the degrees of freedom are strictly translation. The implicit method is compatible to extending to rotational degrees of freedom, but the

SPICE syntax does not readily permit it. In conventional circuit simulators the through variable is current, and the across variable is voltage. From the mathematics, it follows that an analogous relationship can be made with the mechanical variables force and displacement, force being the through variable and displacement being the across variable. Note that other mappings are possible, but the aforementioned is in general the most convenient to implement.

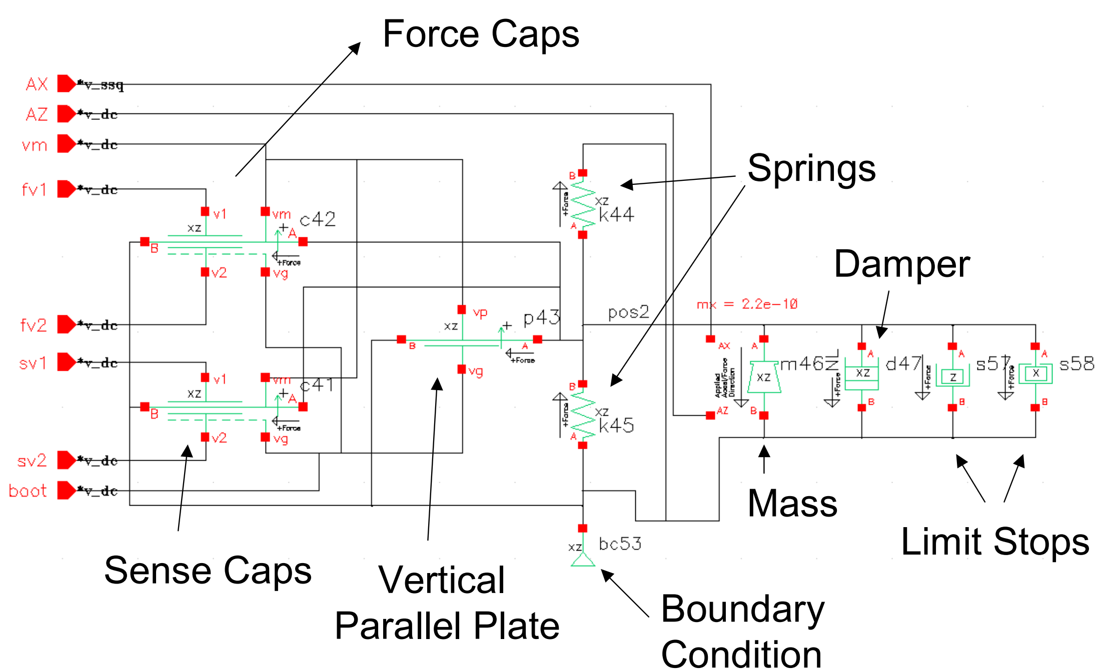


Figure 8: ADXL76 mechanical schematic (2 DOF) implemented in Cadence using Spice models for each individual component.

In the standard electrical engineering definition positive current flow between two nodes is defined as flowing from the higher to lower potential. In the case of the mechanical analogy, we define the force (through variable) as follows: the force through the element is the reaction force on the positively displaced node caused by the element. By using this definition, elements such as negative resistors are avoided, and current direction continues to behave as expected, i.e. it flows from a “high” potential to a “low” potential. The easiest way to remember this convention is as follows: if the current is positive, then the "high" node is being pulled towards the "low" node. Conversely, if the current is negative, then the "high" node is being pushed away from the "low" node.

Circuit simulators are generally tuned to deal with units for volts and amps, which are common in VLSI electronics. A direct mapping to the position and force for MEMS can result in values of the fundamental solution variable, which are significantly out of the range of what is normally expected by SPICE. To alleviate this problem, all macromodels include scaling parameters for both position and current, which enable the user to scale the fundamental solution variables. For the types of problems solved at Analog Devices this scaling parameters are both about 10^{-6}.

Nonlinear components were developed for the damping and the capacitor elements. The initial damping and capacitor models were simple small signal models. The damping model, for example, was simple viscous damping where the gap dimension was not included. By including the gap in the model for damping (e.g. squeeze-film damping is proportional to gap^{-3}), the damping resulting from large motions of the mass was modeled.

The large displacement accurate capacitor models also require a nonlinearity which is given by the well know parallel plate capacitor equation.

$$C(x) = \frac{\varepsilon A}{(d - x)} \tag{1}$$

In the original mechanical schematic 2DOF capacitor model the results from a group of 3D BEM simulations were curve fit to a polynomial. While this was readily implemented in SPICE, it was not accurate for large displacements. A small current feedback loop was used within the new capacitor model to implement the nonlinear capacitance, which would be valid over very large deformations. A similar feedback loop was used for the nonlinear force that is generated across the air gap capacitor.

Figure 9 shows the results of an overload acceleration of 2000g in the y-axis applied to the ADXL76. Both the small-signal and large-signal model results are displayed. The small-signal results show no indication of the mass hitting the limit stops

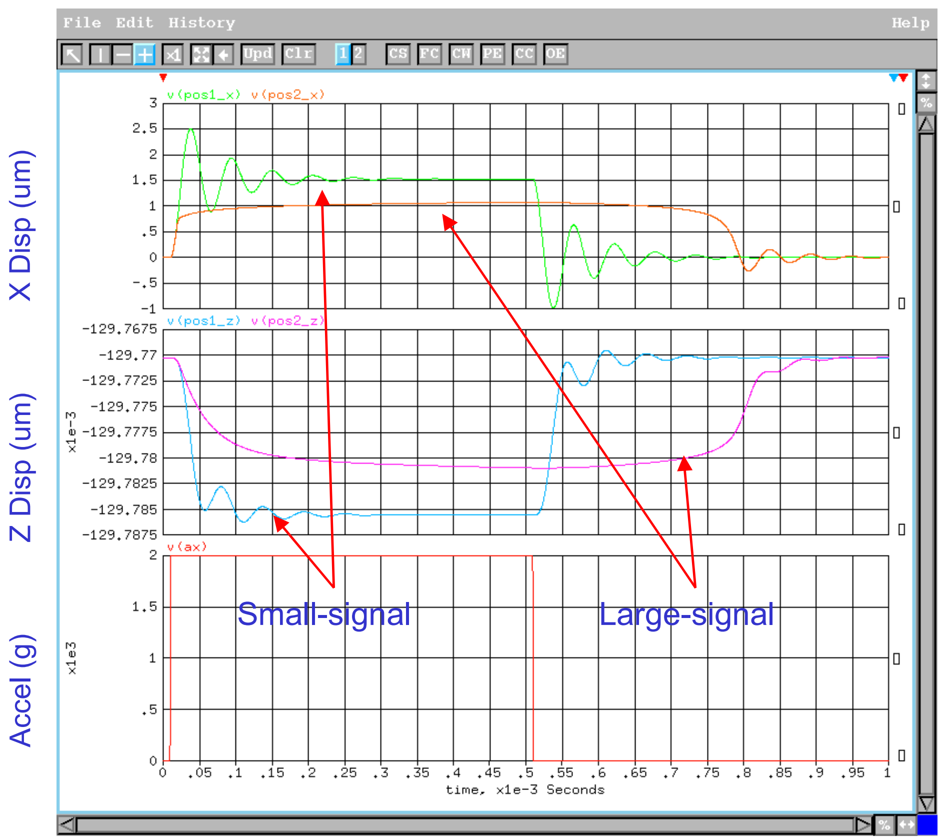


Figure 9: Response of mechanical schematic model of ADXL78 accelerometer to a 2000g overload. Demonstrates the implementation of nonlinear damping.

at about 1.2µm while the large-signal models show a large increase in the damping to the extent to which the mass does not begin to spring back after the acceleration impulse has ended. To be fair, hard limit stops were removed from the small signal model as they are non-physical, but even with the limit stops present the small signal model would respond immediately after the acceleration impulse ended. Note also the cross axis sensitivity that is shown by the z-axis response. This arose from the 2 DOF model for the capacitance that was obtained from 3D BEM simulations.

1.2.3.2 Verification of MEMS: DRC & LVS

A vital requirement in the efficient design and layout of an integrated MEMS device is the verification that the layout of the device is indeed what was modeled and simulated. In electronic CAD design rule checking (DRC) and layout versus schematic (LVS) checks are applied to insure that the design doesn't violate process design rules and that the layout of the transistor/capacitor/resistor is of the appropriate size and connectivity.

Implementation of a full mechanical equivalent of LVS proved to be beyond the abilities of this project. However, several very useful tools were created in the Cadence environment to facilitate the verification and checking of the MEMS device layout. These tools; MemsXView, MemsCheck, and Memsdbx, were made available for licensing from Microcosm, but to date they have not been including in any release of MEMCAD or CoventorWare.

1.2.3.2.1 MemsXView

MemsXView provides the ability to map port connectivity between layout and schematic. Part of the normal LVS flow is the extraction process. During extraction all of the devices and all the connectivity between the devices are identified. Since we were not able to extract the MEMS device directly we incorporated labels in the layout to identify specific parts. The labels provided the connectivity. Unfortunately, while this insured that things were connected correctly it was still subject to human error, as an engineer must manually place the labels. Better would be to automatically extract the MEMS device and thus all of the connectivity. MemsXView is the skill code front-end to Memsdbx that allows graphical cross-probing to help quickly identify the errors.

1.2.3.2.2 Memsdbx

Memsdbx is the Dracula runset, which determines the connectivity of the MEMS device. This runset can also be thought of as implementing ERC – electrical rules checks. As mentioned above this method of manually placing labels is subject to human error and thus not robust, but it is much better than what we had before, which was no software verification.

1.2.3.2.3 MemsCheck

MemsCheck is collection of skill code to check the symmetry of the MEMS device about difference axes. Specific layers could be selected and tested against the X or Y-axes. MemsCheck also implemented a mass calculation as well as an area and perimeter calculation for the complex shapes of MEMS devices. This was used to verify that the mass used in the macromodel was indeed what was represented in the layout.

1.2.3.3 Modification of Autobem™ tool for Macromodeling

During the course of this project it was becoming increasingly clear that the accurate simulation of overload operation of accelerometers and gyroscopes was critical. The ability to model this type of input enables both improved designs as well as their insertion into many new applications (e.g. smart munitions). In this application, the initial acceleration is many times the full-scale resolution of the part. It is necessary to know the performance of the part during and after the initial acceleration and that acceleration measurements are accurate once the input acceleration is below full-scale. Also, we need to accurately know how well the devices handle momentary, few times full scale, over-range shocks while in operation. We have found that due to the desirably small size and standard IC mounting of ADI devices we respond to mechanical shocks naturally present in many systems that other more bulky devices tend to damp out due to their size and other specialized mounting.

Towards these ends an alternate simulation engine was explored with a subcontract with Coyote Systems. The subcontract added features to Coyote System's software Autobem™ to make it a more useful macromodeling tool for real-world design. Autobem™ has been found to be easy to use, accurate, and fast in simulating electrostatic problems. Unlike other software packages available, this tool has both a batch language as well as an adaptive-meshing routine that works very well. Autobem™ was used extensively in the capacitance simulations of the ADXL190 and ADXL78. This was very challenging as we were interested in the change in capacitance that is 1% at full-scale. We required 1% accuracy on a 1% change in capacitance or 100ppm. Most electrostatic simulators have serious problems achieving this level of accuracy because of the mesh and time required. Autobem™ eliminated both of these issues. The recently released ADXL78 accelerometers, which used Autobem extensively, have very tight sensitivity distributions thus proving the success of the capacitive modeling.

Nevertheless, Autobem™ was not designed for macromodel extraction. The plan was to make the necessary changes to the code to automate macromodeling. The primary changes involve the modifications of the geometrical representation of the problem within Coyote's data structures. This would allow Autobem™ to create macromodels that incorporate the manufacturing variations of the structure (e.g., width, thickness, length). Fortunately, the initial data structure was very compatible with this change. The BEM mesh was already relative to the solid model geometry. All that was required was to add a few changes so that the geometry could be easily deformed mathematically.

The geometry modification ability combined with the batch-language interface with Autobem made creating macromodels much easier. Without these features, a user was required to modify the layout, re-enter the data into Coyote software, and then re-use the adaptive-meshing technique to achieve an optimal mesh. This takes additional time and requires user input and is thus also subject to error. This process however cannot model out-of-plane motion such curvature in the structural layer.

Figure 10 shows the application of the macromodeling on the curvature of the ADXL76 accelerometer. As with MEMCAD™ the solid model is generated from a

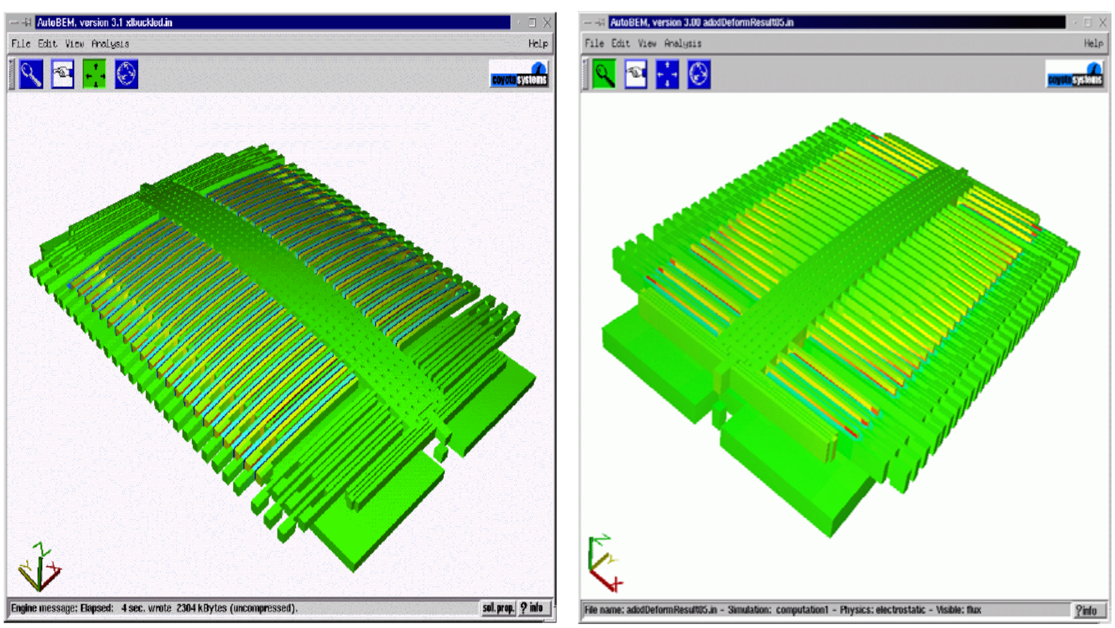


Figure 10: Macromodeling using AutoBEM™ - warpage of ADXL76 accelerometer and resulting charge distribution.

physical layout and a process description file. The electrode names can be identified in the layout program. This eliminates the need to "pick" all of the electrodes after the solid model is created. Next, the boundary conditions are established and the simulation is specified. Finally, the solver is launched with adaptive mesh refinement to a given criteria such as the change in change on a given electrode changes less than a given percent from the previous solution. When completed a number of parameters can be displayed or extracted: electrostatic change and flux, force and torque in and about the coordinate axes.

Figure 11 shows an example of a batch input file for the exaction of capacitance over the space of transformations of the mass in x, y, and z as well as the curvature of the mass. The central function is the `deform` command as well as the `print` command. `deform` uses a function called `rpn`, which provides a confusing stack based mathematics. Any standard mathematical transformation can be created with this command including transcendental functions. The print command outputs the resulting parameter (e.g. capacitance) to the log file. Unfortunately, there was no GUI interface built around the output. The user is required to parse the log file and then curve fit the results, which is typically performed in Matlab. However, this worked well in concert with the capacitors in the mechanical schematic described in Section 1.2.3.1.

```
(* #!BEMEngine{id{3.1}}; *)
forEach{
 fileName{xlgeom1.in , xlgeom2.in, xlgeom3.in  }, (* specify the input files here *)
 {get{file{fileName}},
  forEach{regionName{"fa","fb","sa", "sb","mov", (* "gnd" *) },
   {simulationSpecification{
        (* here we create a simulation specification with the engine defaults *)
     name{ regionName }, boundaryCondition{physics{electrostatic},
     type{criticalNet, netList{"fa","fb","sa","sb","mov","gnd"}}, (* end type *)
     region{regionName},}, (* specify which region is on potential 1 here *)
     domain{
      physics{electrostatic}, type{default}, volume{"outside"}, material{"air"},
      acceleration{ localExpansion{3}, eta{0.7} },},
    }, (* end simulation spec. *)
    forEach{
     warpRadius{1e2, 3e2, 5e2  }, (* specify warp radia here *)
     {forEach{xtrans{-1e-7, -2e-7  }, (* translation in x direction *)
       {forEach{ytrans{-1e-7, -2e-7 }, (* translation in y direction *)
         {forEach{ztrans{-1e-7, -2e-7  }, (* translation in z direction *)
           {resetMesh{ simulationSpecification{regionName} },
            refine{simulationSpecification{regionName},
             tunnel{regionList{regionName},tunnelRadius{3e-06},
              resolveTunnelEdge{true},insideRefinement{type{noRefinement}},
              outsideRefinement{type{delete}},},
            }, (* end tunnel refine *)
            refine{simulationSpecification{regionName},
             elementSize{ type{ h }, absolute{ 0.5e-12 }, }}, (* end size refine *)
            refine{simulationSpecification{regionName},
             elementAspectRatio{ type{ h }, absolute{ 15 }, }}, (* end aspect refine *)
            deform{simulationSpecification{regionName}, clear{}, },
            deform{simulationSpecification{regionName},
             value{option{ excludeRegion{"gnd"} },
              RPN{0},RPN{0},RPN{RPN{25e-6,y,-,25e-6,y,+,*,warpRadius,*},RPN{19e-6,x,-
,19e-6,x,+,*,warpRadius,*},*,5e7,*}}}, (* warping function in the z direction *)
            deform{simulationSpecification{regionName},
             value{option{ excludeRegion{"gnd"} },
              RPN{xtrans},RPN{ytrans},RPN{ztrans}}}, (*translations in x,y and z *)
            solve{ simulationSpecification{regionName}, solver{GMRES},
             preconditioner{blockDecomposition} },
            print{...}, (* print the values we are observing, preceeded by user tag *)
            (* the following repeat does the error based adaptive refinement *)
            repeat{ command{
              refine{ simulationSpecification{regionName},
               elementErrorIndicator{ type{ h }, statistical{elementFraction{0.25}} } },
              solve{ simulationSpecification{regionName}, forceSolve, solver{GMRES},
               preconditioner{blockDecomposition} },
              print{...}, (* end command block *)
             succeed{RPN{RPN{delta{solution{integralValue{
                   quantity{chargeDensity,physics{electrostatic}},
                   simulationSpecification{regionName},region{regionName}}}}},abs},
                   0.005,<}}, (* end succeed *)
             fail{ RPN{iteration, 15, > } },}, (* end repeat block *)
            print{...}, (* end print *)
           }, (* end forEach ztrans  *)
          }, (* end forEach ztrans commands *)
         }, (* end forEach ytrans  *)
        }, (* end forEach ytrans commands *)
       }, (* end forEach xtrans  *)
      }, (* end forEach xtrans commands *)
     }, (* end forEach warp  *)
    }, (* end forEach warp commands *)
   } (* end forEach regionName commands *)
  } (* end forEach nameName  *)
 } (* end forEach fileName commands *)
}; (* end forEach fileName *)
```

Figure 11: Batch language of Autobem™ showing implementation of the `deform` command which allows the geometry to be deformed by a generic mathematical transformation. See Autobem™ manual for a detailed description.

1.2.4 Application of New Tools in Real Designs

1.2.4.1 ADXL190

The first application of the MEMS CAD tools that were developed during this contract is to the design of the ADXL190, a 250g lateral accelerometer. The motivation for the ADXL190 was that accelerometers were moving away from the center module and to the periphery of automobiles. These satellite sensors would need to measure much higher acceleration levels because there was less material to adsorb the crash energy between the point of impact and the sensor. The challenge was to start with the well-established ADXL76 50g accelerometer and in the most rapid, yet robust method, design a 250g version. Figure 12 shows a picture of the MEMS structure used for the ADXL76/190. It was quickly realized that swapping the sense (42) and self-test force

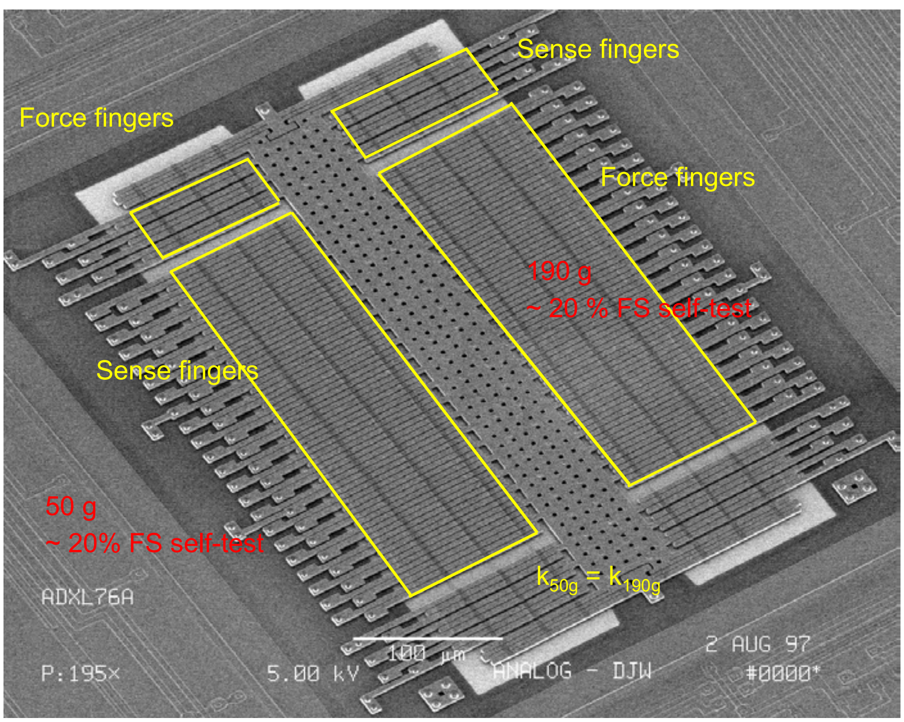
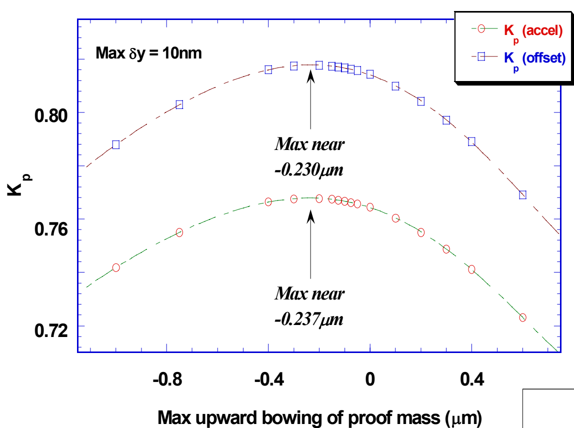


Figure 12: ADXL190 - 250g version of ADXL76 with sense and force capacitor fingers swapped.

(12) capacitive fingers would achieve approximately the correct sensitivity.

There were many concerns about such a simple change but the major one was the impact on the capacitive sense transfer function and the resulting sensitivity laser trim. Figure 5 shows the BEM model of MEMS structure that was used to determine the effect of curvature on the resulting sensitivity (z-displacement resulting from curvature of is plotted). Figure 13 shows the resulting calculations for Kp, the amount sensitivity is reduced from the parallel plate approximately by the fringing fields. Because of the placement of the fingers the maximum sensitivity occurred when the mass bowed towards the substrate. The resulting variation in Kp was determined to be compatible with the laser trim of sensitivity, which ended up being approximately 10% lower (i.e. more gain was required.



- Curvature impact on sensitivity (max & 0.2um)

- Sensitivity trim (fewer fingers, 10% lower)

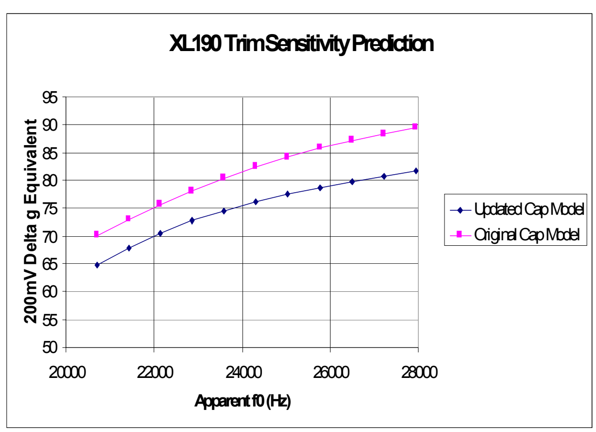


Figure 13: Results from application of MEMCAD tools to ADXL190. Curvature impact on sensitivity (Kp). Sensitivity trim of SiCr resistors was 10% lower.

1.2.4.2 ADXL78

The ADXL78 is the 4th generation 50g lateral accelerometer at Analog Devices. The primary considerations were in reducing the cost (i.e. the size) of the part as well as producing a sensor that was more robust to overload conditions. The final embodiment of the sensor was actually two single-axis lateral accelerometers that are measured differentially. The area of the two sensors is about 70% of the ADXL76 sensor and the overall chip area was reduced by half.

Autobem and the mechanical schematic were used extensively in the development of the MEMS structure. The impact of these tools can be seen by the fact that the sensitivity as measured on actual devices was within a few percent of the designed and simulated value. This product because of the much higher overload specifications motivated the modifications to the mechanical schematic, incorporation of nonlinear capacitance and damping.

1.2.4.3 SPCMems – Modeling Process Corners

A preliminary evaluation of the SPCMems methodology was performed. That methodology varied the solid model geometry based on understood process variations and then created AutoMM™ models for each of these geometries. In this way, models that spanned the process variation space were developed to yield simulation results spanning the space. However, given the large number of FEM/BEM simulations required for each of these AutoMM™ models, this methodology proved difficult to use. The advent of the PEM models allowed a much more computationally efficient way to perform the same exploration of the process variation space. Figure 14 thru Figure 16 show three different examples of the application of AutoMM™ to a tethered plate. These types of real life issues: process variations, mismatches, and misalignments are absolutely critical for the successful design of high performance and highly yielding MEMS systems.

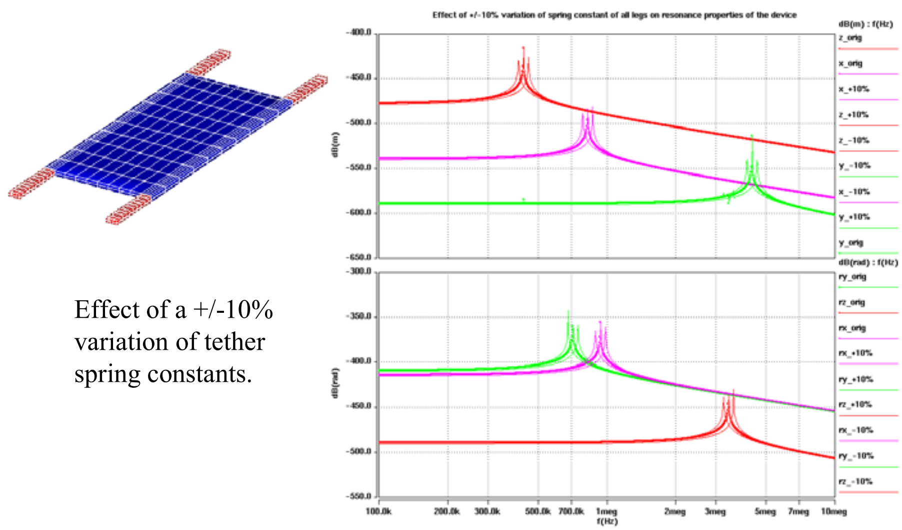


Figure 14: SPCMems – tether spring constant variation.

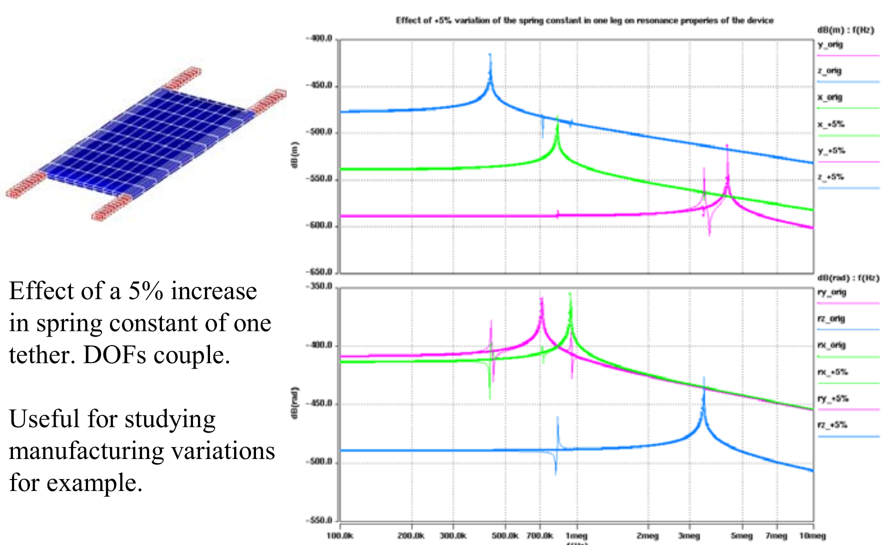
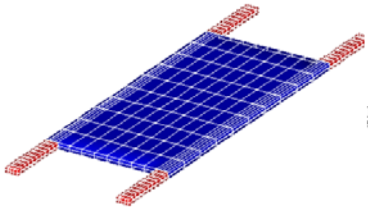
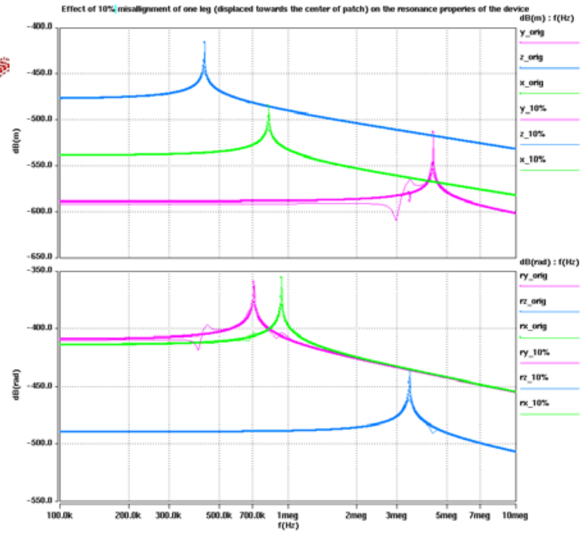


Figure 15: SPCMems - tether mismatch. Creates unintended cross-axis effects.





Effect of 10% misalignment of position of one tether.

Useful for packaging studies for example

Figure 16: SPCMems - misalignment of tether anchor. Very useful for exploring packaging effects.

1.2.5 Uniform Design Environment for Integrated MEMS

Towards the end of the program Coventor and Analog Devices realized that while the software, which had resulted from this program, did meet the program's objectives it could be greatly enhanced by porting it to a design environment that was more compatible with circuit simulation. This would allow both the reduced order models of MEMS devices and the integrated electronics to be simulated inside of a more widely used circuit simulator. The choice of environment was Cadence using the SpectreRF™ simulation tool, which is based on Verilog-A. While Saber can simulate circuits it was originally developed as a system level tool. This legacy, and the resulting public image, has prevented Saber from being utilized widely by the industry. Cadence is clearly the dominant EDA tool on the market today and was thus the obvious choice. It should be pointed out that the Cadence/SpectreRF™ interface with the AutoMM™ and PEM models has continued beyond the end of the original contract and is now subject to an agreement between Analog Devices and Coventor. Nevertheless, the results which have been achieved to the date of this final report are included as they are directly related to the initial object of this program – development of an integrated MEMS design environment.

In the Cadence/SpectreRF implementation the engineer would have both Cadence and CoventorWare™ running. The links between Cadence and CoventorWare™, such as layout to schematic conversion (AutoMM™) and schematic to layout generation, are created with Cadence skill code as well as interface code in CoventorWare™. The two major pieces of work were around he port of the AutoMM™ and PEM libraries from MAST™ to Verilog-A and the implementation of a Cadence interface to these models.

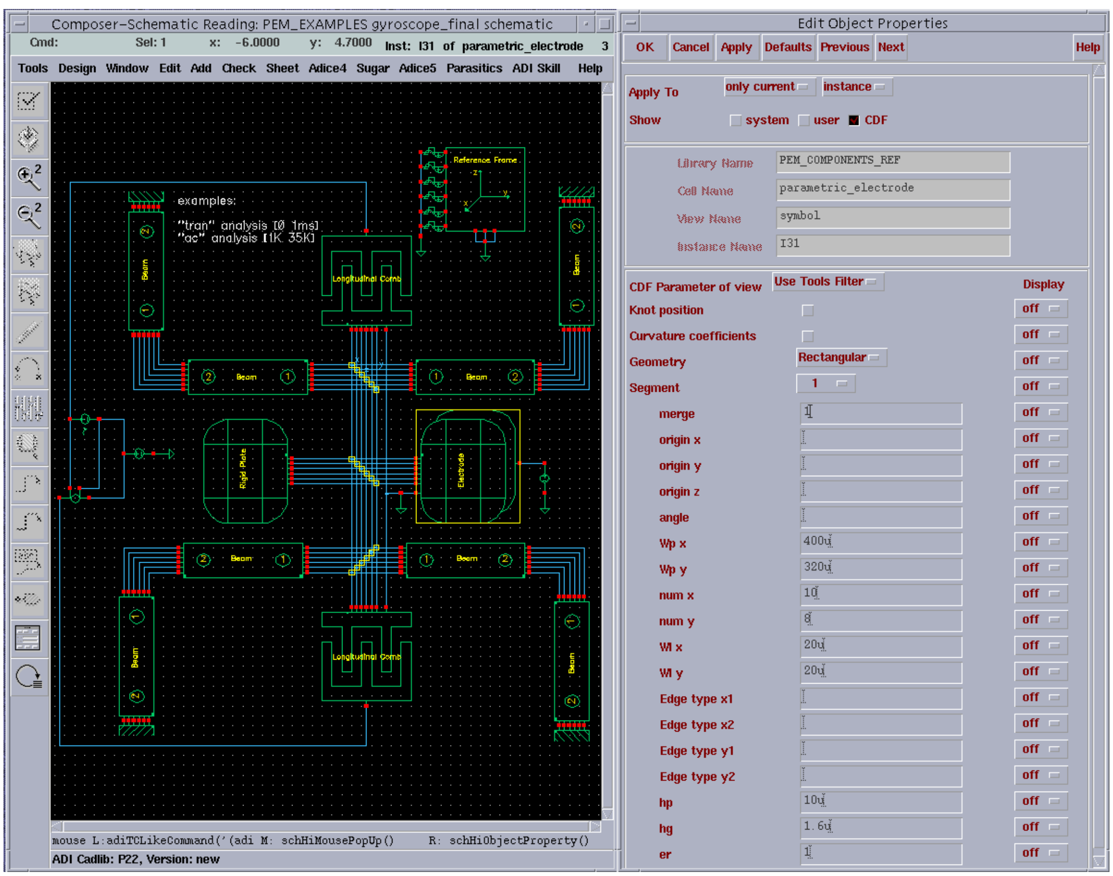


Figure 17: Example of a gyro using MEMCAD™ models applied in a Cadence design environment. The properties of the electrode element are shown on the right.

Both MAST™ and Verilog-A are HDL languages so conversion was relatively straightforward. This harder problem was interfacing with Cadence. This was primarily through the parameters window for a given object (e.g. beam or plate in PEM library). Incorporating the parameters in an efficient and user-friendly way was the problem.

Figure 17 and Figure 18 show two examples of the Cadence implementation of the PEM library. The parameter window of an electrode and beam element are also shown to demonstrate the complexity of this implementation. Figure 19 shows an

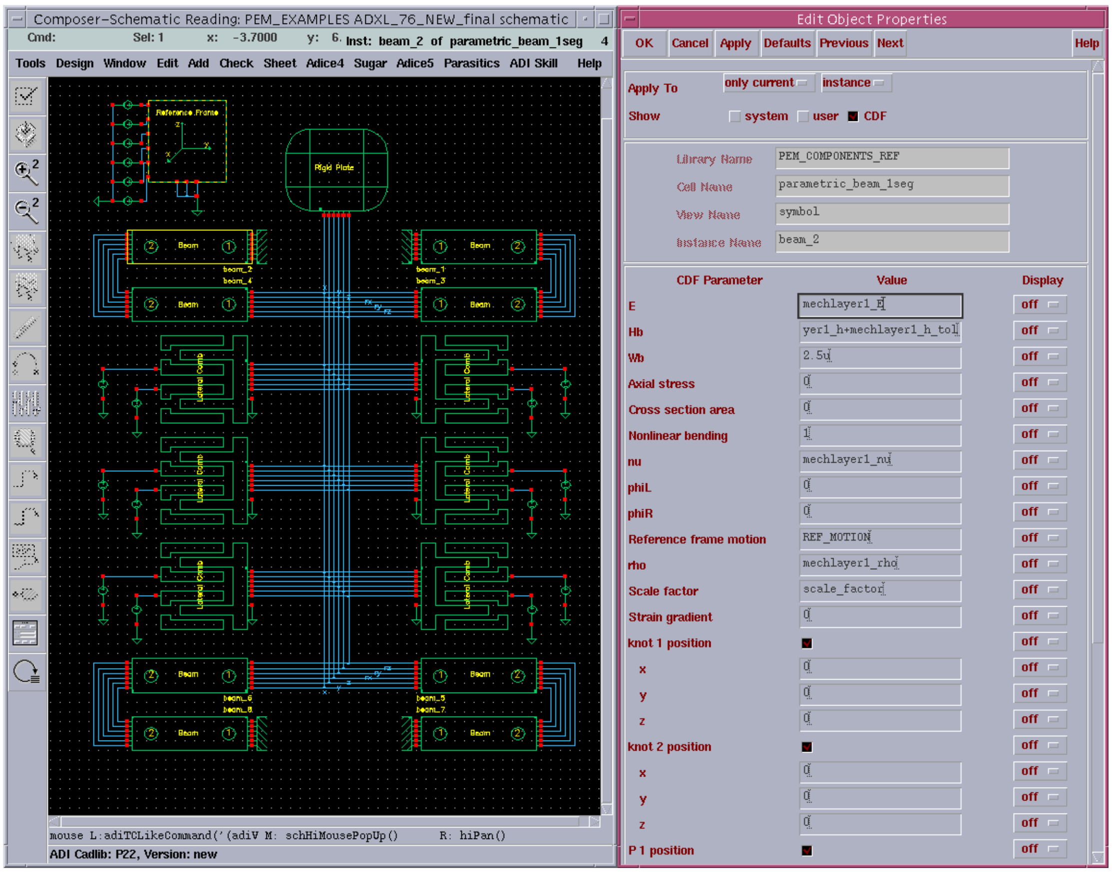


Figure 18: ADXL76 implemented using PEM library parameters in the Cadence environment. The properties of the 1 segment beam element are shown on the right.

example of the SpectreRF™ interface to a gyroscope. The simulation that is shown is an AC analysis. This embodiment of the Cadence/CoventorWare™ interface requires the use of at least Cadence version 4.4.6 and CoventorWare™ 2001.3.

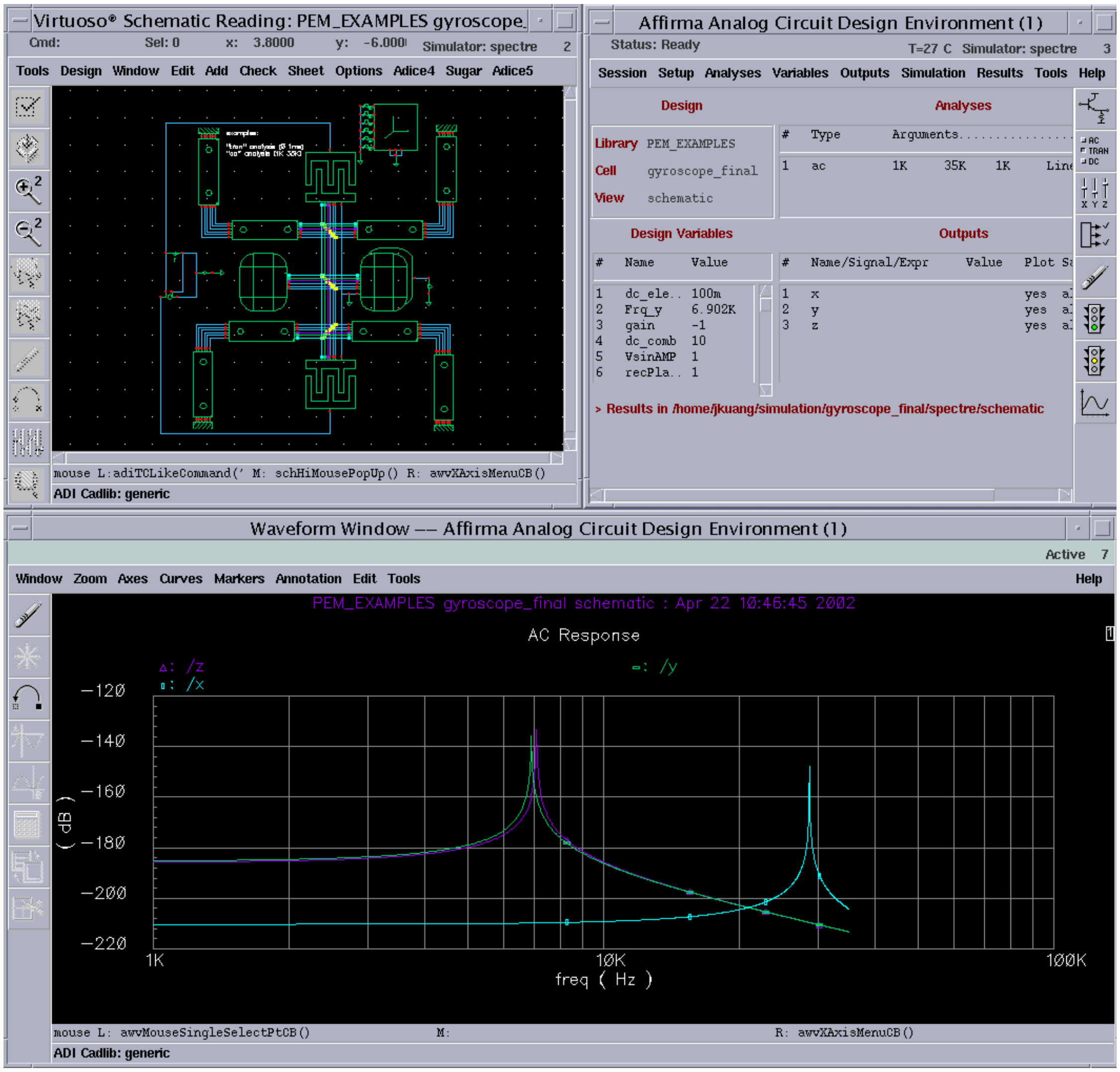


Figure 19: Example of SpectreRF™ interface to macromodels in Cadence design environment - Gyroscope.

A validation report has been developed to demonstrate the accuracy of the PEM and AutoMM models in the Cadence/SpectreRF™ design environment through detailed comparison with Architect™ simulations (Saber environment), simulation data (3D FEM/BEM) and experimental data. The purpose was to present the correlation between the models and actual experimental data and/or 3D simulation result, on a handful of carefully chosen cases defined in the validation plan in order to provide confidence for Coventor and Analog Devices that PEM and AutoMM models are a viable design methodology that will greatly shorten time-to-market and greatly increase the change of first silicon success in the product development process.

The objectives of the validation plan were to evaluate the design environment, simulation speed and performance. In order to meet the objectives outlined, four validation tasks were identified (Table 1). Comparisons between the PEM and AutoMM™ models and the measured data set will be conducted. Although the final version of the validation report is as of yet not available it has already demonstrated that most of the AutoMM and PEM models agree with the Saber™ simulation results as well as FEM/BEM simulations. The test structures which were designed are currently being fabricated. The final validation report should be available in Summer 2002. The reader is encouraged to speak with Coventor then as this report contains a wealth of information about the validity of the macromodels as well as the regions of appropriate applications of the models (i.e. where the implicit approximations are valid).

Table 1: Validation criteria.

Name	Structures	Description	Variation
VP1	Elemental Devices-Mechanical	Comparison of mechanical response of some PEM library components with FEM simulations	Cantilever Beam
			FF Beam-center loaded
			FF Beam-uniform loaded with axial
			FF Beam-uniform loaded with axial
VP2	Elemental Devices-Electrostatic	Comparison of mechanical response of some PEM library components with FEM simulations	Parallel Plate
			Longitudinal Comb
			Lateral Comb
VP3	Test Devices	Comparison of electromechanical response of some PEM library components with 3D FEM/BEM coupled simulations	Torsion Mirror
			Gimbal Mirror (2-axis)
			XL76
			P20

VP4	Test Devices-Measured Data	Comparison of PEM library components with measured data	Cantilever Beam
			FF-Beam
			Torsion Mirror
			Comb Resonator
			Xl76
			P20

1.3 Summary

The MEMSCAD DARPA program was very successful from the perspective of all parties involved. Several new MEMS CAD tools were developed and released to the MEMS design community via MEMCAD™ 4.0 and eventually CoventorWare™ as well as AutoBEM. The primary development was AutoMM™ which established the first automatic reduced order model extraction tool. To enable AutoMM™ the BEM capacitance solver needed to be enhanced to solve real-world problems like accelerometers and gyroscopes. Eventually this led to the development of the parameterized electromechanical library (PEM library) as well as the schematic to layout generator in MEMCAD™.

Analog Devices also greatly improved the macromodeling capabilities in SPICE through the development of the mechanical schematic (Cadence) and the enhancement of AutoBEM to extract macromodels of complex MEMS capacitors. The verification of the MEMS was improved through the development of MemsXView, MemsCheck and Memsdbx, but the goal of a full mechanical LVS system was not achieved.

The newly developed MEMS CAD tools were applied to the ADXL190 and ADXL78 and contributed significantly to their success. The MEMS CAD tools were verified by comparing the simulations with measured results from test structures that were designed during the course of this project. Both the PEM library and AutoMM™ demonstrated the impacts on MEMS of process variations devices. This allows the user to determine which parameters are most sensitive and to both focus process engineering to improve critical steps as well as instruct the MEMS design on which parameters to design around.

Finally, the project came full circle and by porting the PEM and AutoMM™ models to Verilog-A models and by building a Cadence interface to the models a uniform design environment for integrated MEMS was developed. This last project is now subject to a separate contract between Coventor and Analog Devices and will be completed this summer. When complete this uniform design environment will be made available to the public through a new release of CoventorWare™.

For a more detailed description of the software tools that were developed the reader is directed to contact Coventor directly (www.coventor.com). The manuals for CoventorWare™ are very detailed and contain many examples of MEMS components like gyros, accelerometers and torsional mirrors. DC, AC and transient coupled simulations are fully documented to help reduce the learning time.

1.4 Publications

The following are a list of the publications directly resulting from the work on this program. There are many other publications, which have used the code developed during this program, but they will not be listed here.

1. N.R. Swart, S.F. Bart, M.H. Zaman, M. Mariappan, J.R. Gilbert, and D. Murphy, “AutoMM: Automatic Generation of Dynamic Macromodels for MEMS

Devices," in Proceedings of the IEEE Eleventh Annual International Workshop on Micro Electro Mechanical Systems, Heidelberg, Germany, Jan. 25-29, 1998, pp. 178--183.

2. Zaman, M.H., S.F. Bart, V.L. Rabinovich, C.K. Ghaddar, I. Tchertkov, and J.R. Gilbert, "A Technique for Extraction of Macro-Models in System Level Simulation of Inertial Electro-Mechanical Micro-Systems", in Technical Proceedings of the Second International Conference on Modeling and Simulation of Microsystems, San Juan, Puerto Rico, April 19-21, 1999, pp. 163-167.
3. Zaman, M.H., S.F. Bart, J.R. Gilbert, N.R. Swart, M. Mariappan, "An Environment for Design and Modeling of Electro-Mechanical Micro-Systems", Journal of Modeling and Simulation of Microsystems, 1, 1999, pp. 65-76.
4. Bart, S.F., N.R. Swart, M. Mariappan, M.H. Zaman, and J.R. Gilbert, "An Environment for MEMS Design and Varification", in Technical Proceedings of the 1998 International Conference on Modeling and Simulation of Microsystems Semiconductors, Sensors and Actuators, Santa Clara, CA, April 6-8, 1998, pp. 386-391.
5. Romanowicz, B.F., M.H. Zaman, S.F. Bart, V.L. Rabinovich, I. Tchertkov, S. Zhang, M.G. da Silva, M. Deshpande, K. Greiner, J.R. Gilbert, S. Cunningham, "A Methodology and Associated CAD Tools for Support of Concurrent Design of MEMS", Journal of Computer Modeling in Engineering and Sciences, vol. 1, 2000, pp. 45-63. (Invited)

2 Business/Financial Aspects of the Agreement

2.1 Total Costs Incurred

ADI signed up for a cost share of $723,004, or 24.55% of a total estimated cost of $2,945,382. By the summer of 2001, we were a bit underspent on our cost share but have now caught up—actually exceeded the $723,004 contractually obligated amount.

In February 2002, DCAA sent one of their auditors (Simon W. Leung) to Analog Devices to audit the incurred cost of the MEMS CAD program. Simon reviewed our cost-collection system, backup documentation, management controls, and sample tested a random selection of invoice data. We believe that he was satisfied that everything was in order, although we haven't seen his audit report.

Simon was shown a draft copy of Public Voucher no. 35 (zero dollar invoice), whereby Analog Devices documented that its cost share had been met. Since this was a draft and it was for zero dollars, Simon did not include draft voucher 35 in his audit. Nevertheless, voucher 35 has since been submitted to DCAA Boston in the required manner.

At the final tally, ADI had spent $844,268.21, or 27.51% of the final actual total cost of $3,069,101.11. The Government share at the final tally was $2,033,253.00 or exactly equal to the contractual amount. Microcosm Technologies, Inc. (now called Coventor, Inc.) also exceeded their contractual amount of $189,125 by spending $191,579.90.

2.1.1 Estimated Cost per Contract

Total Estimated Cost of Project	$2,945,382.00
DARPA Share of Estimated Cost	$2,033,253.00
ADI Share of Estimated Cost	$723,004.00
MTI Share of Estimated Cost	$189,125.00

2.1.2 Final Actual Costs per Vouchers

Cost Element			Cumulative Hours/Costs
Analog Devices	Hours		9,593.00
	Unburdened Labor		330,511.77
	Masks		0.00
	Wafer Fabrication		0.00
	Consultant Fees		6,274.13
	Computer Software License & Maintenance Fee		345,550.00
	Reverse: costs (labor) in excess of allocation		-
	TOTAL ADI DIRECT COSTS		682,335.89
	INDIRECT COSTS		
	Engineering Overhead	200.0%	619,199.14
	G and A	35.0%	548,205.29
	TOTAL ADI INDIRECT COSTS		1,167,404.43
	TOTAL ADI PROJECT COSTS		**1,849,740.32**
	DARPA share of Allowed ADI Expenditures	0.00%	**1,005,472.12**
	ADI Share of Allowed ADI Expenditures	100.00%	**844,268.21**
Microcosm Technologies, Inc.			
	TOTAL MTI PROJECT COSTS		**1,219,360.79**
	DARPA share of Allowed MTI Expenditures		**1,027,780.89**
	MTI Share of Allowed MTI Expenditures		**191,579.90**
Cost Share Distribution		(% of Cum.)	
	DARPA, INVOICED	66.25%	**2,033,253.00**
	Analog Devices, Inc.	27.51%	**844,268.21**
	Microcosm Technologies, Inc.	6.24%	**191,579.90**
	TOTAL EXPENDITURES	100.00%	**3,069,101.11**